

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Fire, Earth, Water, Iron

Harnessing the elements to study Nature's most elusive elementary particle.

Mary Bishai
Brookhaven National Laboratory



Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

- 1 Neutrinos: A History
- 2 Neutrino Mixing
- 3 Main Injector Neutrino Oscillation Search
- 4 The Daya Bay Reactor ν Experiment
- 5 The Long Baseline Neutrino Experiment
- 6 Summary
- 7 Acknowledgements

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

A BRIEF HISTORY OF THE NEUTRINO

Neutrino Conception

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

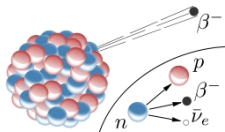
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

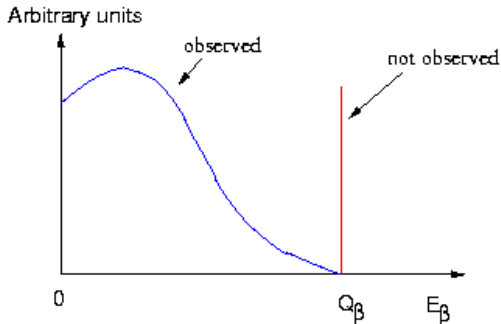
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



Neutrino Conception

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Dec 1930: **Wolfgang Pauli's** letter to physicists at a workshop in Tübingen:



Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

....., I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.....

Unfortunately, **I cannot appear in Tübingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.** With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

Neutrino Conception

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

1932: **James Chadwick** discovers the neutron,
 $\text{mass}_{\text{neutron}} = 1.0014 \times \text{mass}_{\text{proton}}$ - its too heavy -
cant be Pauli's particle



James Chadwick

Neutrino Conception

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

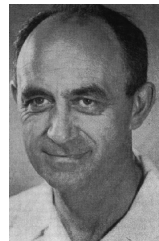
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Solvay Conference, Bruxelles 1933: **Enrico Fermi**
proposes to name Pauli's particle the "**neutrino**".

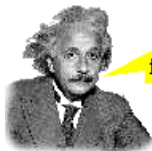


Enrico Fermi

Particle physics units and symbols

Symbols used for some common particles:

Symbol	Particle
ν	Neutrino
γ	Photon
e^-	Electron
e^+	Anti-electron (positron)
p	proton
n	neutron
N	nucleon - proton or neutron



Mass is just a
form of energy!

Particle physicists express masses in terms of energy, $\text{mass} = E/c^2$,
 $\text{mass}_{\text{proton}} = 1.67 \times 10^{-24} \text{g} \approx 1 \times 10^9 \text{ electron-volts} = 1\text{GeV}/c^2$

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Finding Neutrinos...

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

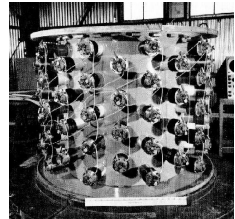
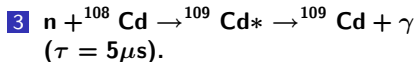
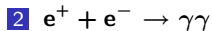
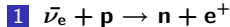
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

1950's: Fred Reines at Los Alamos and Clyde Cowan use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos. A detector filled with **water with CdCl_2 in solution** was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:



Neutrinos first detected using a nuclear reactor!

ν : A Truly Elusive Particle!

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Reines and Cowan were the first to estimate the interaction strength of neutrinos.

The cross-section is $\sigma \sim 10^{-43} \text{cm}^2$ per nucleon (p,n).

$$\nu \text{ mean free path} = \frac{\text{Mass of the proton}}{\sigma \times \text{density}}$$

$$= \frac{1.67 \times 10^{-24} \text{g}}{10^{-43} \text{cm}^2 \times 11.4 \text{g/cm}^3} \approx 1.5 \times 10^{16} \text{m} = \mathbf{1.6 \text{ LIGHT YEARS}}$$

A proton has a mean free path of 10cm in lead

Neutrino detectors have to be MASSIVE

Discovery of the Muon (μ)

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

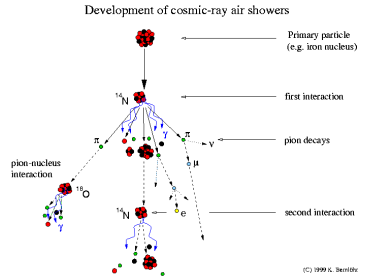
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).



C. Anderson with a magnetized cloud chamber

© Copyright California Institute of Technology. All rights reserved.
Commercial use or modification of this material is prohibited.



Cosmic tracks in a cloud chamber

© Copyright California Institute of Technology. All rights reserved.
Commercial use or modification of this material is prohibited.

The Lepton Family and Flavors

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

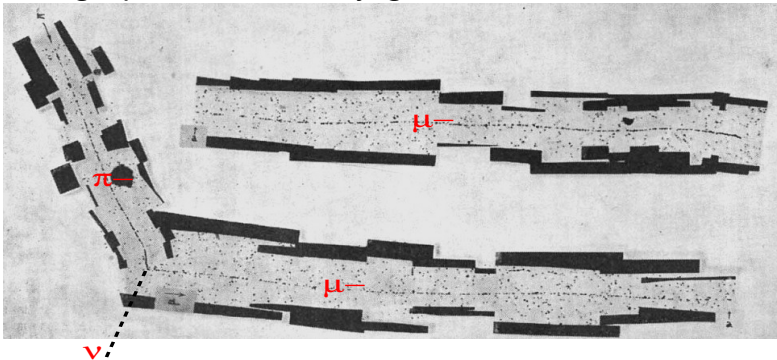
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons.*

Generation	I	II	III
Lepton	e^-	μ	τ
Mass (GeV)	0.000511	0.1057	1.78
Lifetime (sec)	stable	2.2×10^{-6}	2.9×10^{-13}

Neutrinos are neutral leptons. Do ν 's have flavor too?

Discovery of the Pion: 1947

Cecil Powell takes emulsion photos aboard high altitude RAF flights.
A charged particle is found decaying to a muon:



$$\text{mass}_{\pi^-} = 0.1396 \text{ GeV}/c^2, \tau = 26 \text{ ns.}$$

Pions are composite particles from the “hadron” family which includes protons and neutrons.

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Neutrinos have Flavors

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

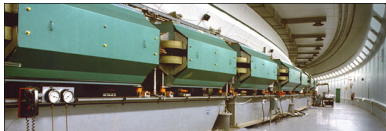
The Long
Baseline
Neutrino
Experiment

Summary

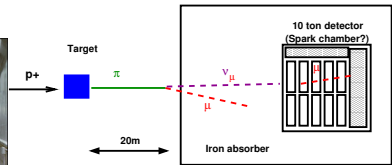
Acknowledgements



1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu \nu_x$



The AGS



Making ν 's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles were identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

The first accelerator neutrino experiment was at the AGS.

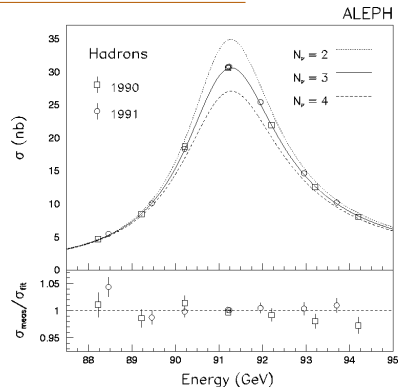
Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

The LEP e^+e^- collider at CERN, Switzerland



The 27km LEP ring was reused to
build the Large Hadron Collider



$$N_\nu = 2.984 \pm 0.008$$

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

The Particle Zoo

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

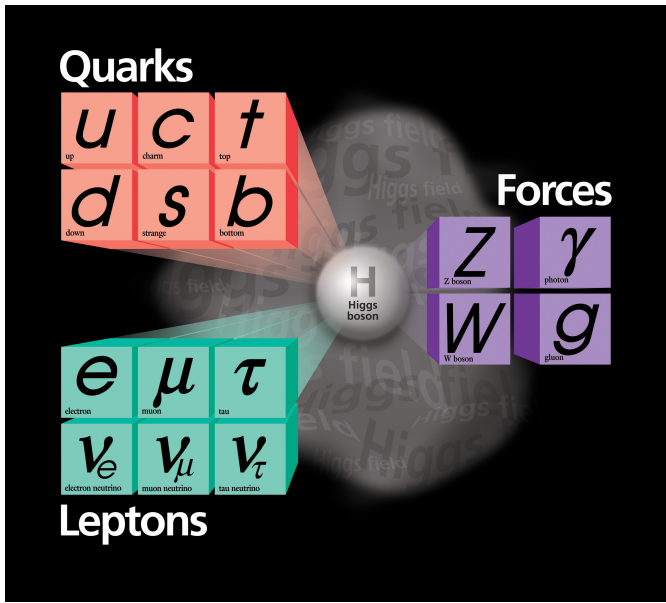
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



Sources of Neutrinos

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

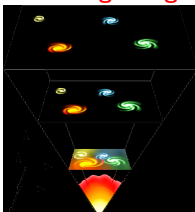
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

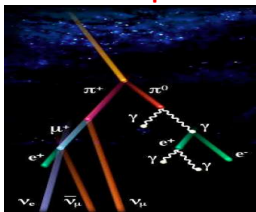
Acknowledgements

Big Bang



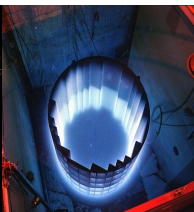
10^{-4} eV
 $300/\text{cm}^3$

Atmosphere



~ 1 GeV
 $\text{few}/\text{cm}^2/\text{s}$

Reactors



few MeV
 $10^{21}/\text{GW}_{\text{th}}/\text{s}$

Accelerators



1-20 GeV
 $10^5/\text{cm}^2/\text{s}$ (at 1km)

Sun



0.1-14 MeV
 $10^{10}/\text{cm}^2/\text{s}$

SuperNova



~ 10 MeV
 $10^9/\text{cm}^2/\text{s}$

Extragalactic



TeV-PeV
varies

Neutrinos and Today's Universe

Neutrino mass < 2 eV (beta-decay limits)

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

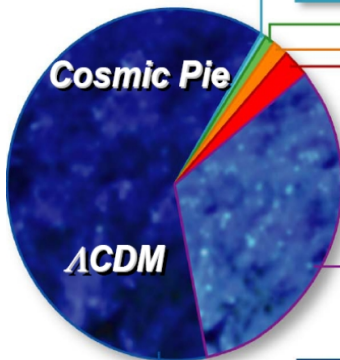
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$



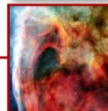
Heavy Elements:
 $\Omega=0.0003$



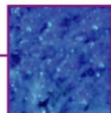
Neutrinos (ν):
 $\Omega=0.0047$



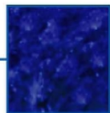
Stars:
 $\Omega=0.005$



**Free H
& He:**
 $\Omega=0.04$



Cold Dark Matter:
 $\Omega=0.25$



Dark Energy (Λ):
 $\Omega=0.70$

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

NEUTRINO MIXING AND OSCILLATIONS

Some Quantum Mechanics

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

1924: **Louis-Victor-Pierre-Raymond, 7th duc de Broglie** proposes in his doctoral thesis that all matter has wave-like and particle-like properties.

For highly relativistic particles : energy \approx momentum



De Broglie

$$\text{Wavelength (nm)} \approx \frac{1.24 \times 10^{-6} \text{ GeV.nm}}{\text{Energy (GeV)}}$$

Neutrino Mixing

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

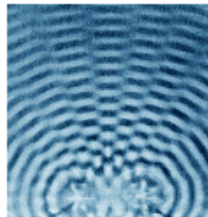
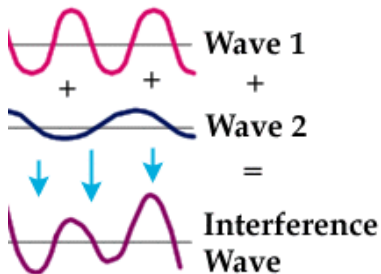
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

1957, 1967: B. Pontecorvo proposes that neutrinos of a particular flavor are a mix of quantum states with different masses that propagate with different phases:



The interference of water waves coming from two sources.

The interference pattern depends on the difference in masses

Neutrino Oscillations

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

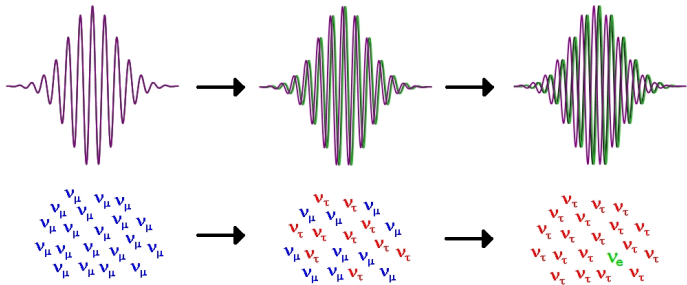
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Neutrino mass states *interfere* \Rightarrow neutrinos **oscillate** between different flavors:



If neutrinos oscillate \Rightarrow neutrinos have mass!

The Homestake Experiment

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

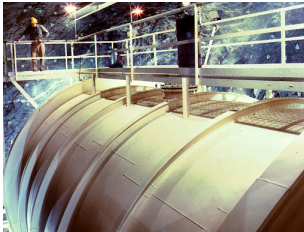
1967: **Ray Davis** from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1 $\nu_e^{\text{sun}} + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$, $\tau({}^{37}\text{Ar}) = 35$ days.

2 Number of Ar atoms \approx number of ν_e^{sun} interactions.



Ray Davis



Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a **ν_e^{sun} deficit of 69%**.

Solar ν_e disappearance \Rightarrow

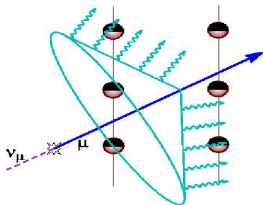
first experimental hint of oscillations

Water Cerenkov Neutrino Detectors

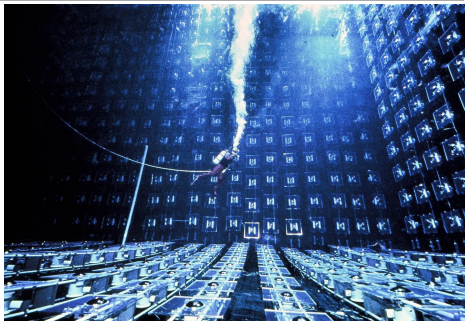
Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

A relativistic charged particle going through water, produces a ring of light



The Irvine-Michigan-Brookhaven Detector



With water, get MASSIVE detectors (kilo-tons)

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

The Super-Kamiokande Detector

Mount Ikeno, Kamioka, Japan

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

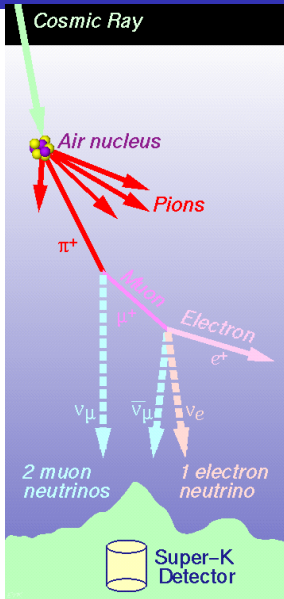
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

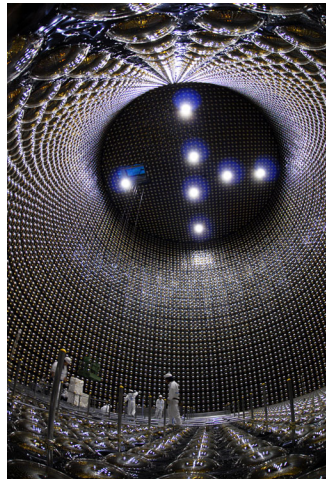
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



A huge **50kT double layered tank of ultra pure water** surrounded by 11,146 20" diameter photomultiplier tubes.



Identifying ν_μ and ν_e Interactions

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

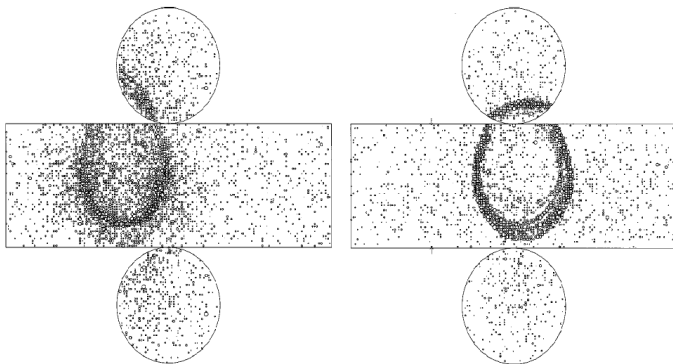
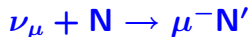


FIG. 24. An e -like (left) and a μ -like (right) event observed in the Super-Kamiokande detector.

KamLAND: Reactor $\bar{\nu}_e$ Detector

Kamioka Mine

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

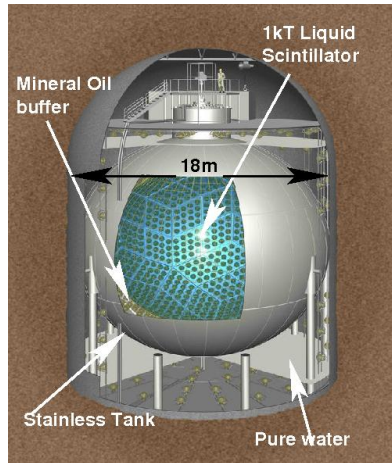
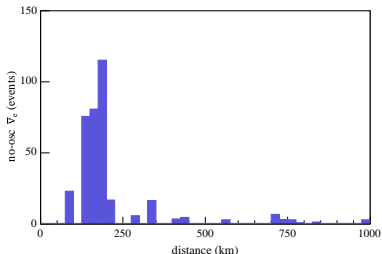
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Japan's electric power is mostly from nuclear reactors, the Kamioka Mine is bombarded by $\bar{\nu}_e$ from reactors:



Neutrino Oscillation Results

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

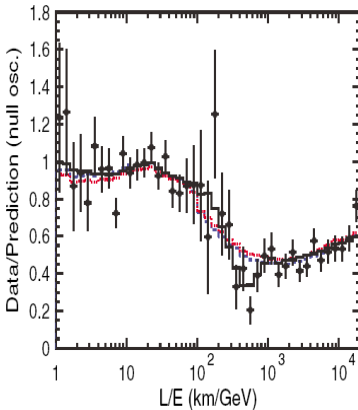
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

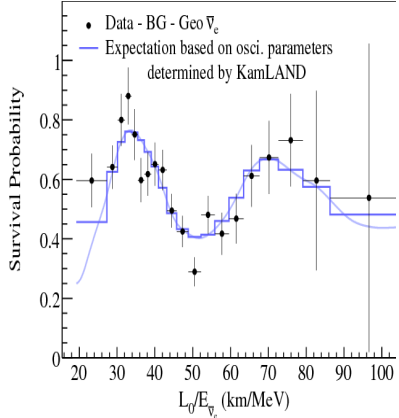
Summary

Acknowledgements

Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Clear wiggles!, different beat frequencies

Neutrino Mixing: 3 flavours

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

**Neutrino
Mixing**

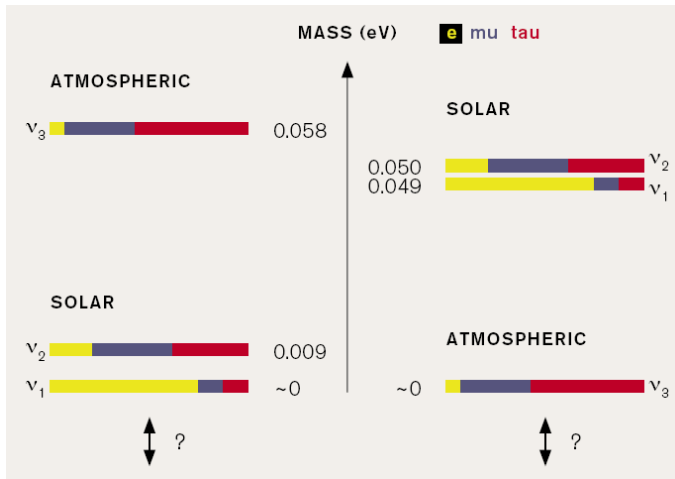
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



The amount of ν_e state in ν_3 is unknown, but is constrained to be $< 4\%$

We don't know which is larger m_3 or m_1 .

Charge-Parity Symmetry

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Charge-parity symmetry: laws of physics are the same if a particle is interchanged with its anti-particle and left and right are swapped.

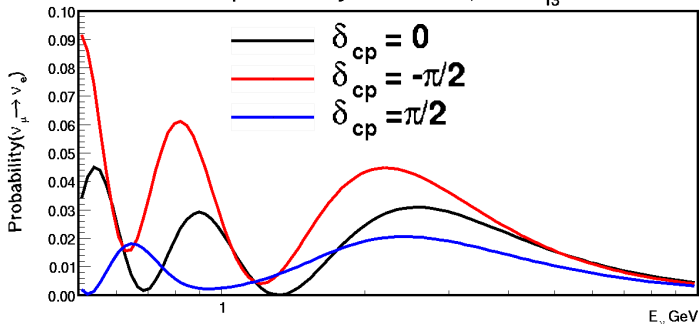
A violation of CP \Rightarrow matter/anti-matter asymmetry.



Charge-Parity Symmetry and Neutrino Mixing

There are 3 quantum states mixing \Rightarrow there is an overall phase: δ_{CP} .

Oscillation probability at 1300km, $\sin^2 \theta_{13} = 0.01$



If $\delta_{CP} \neq 0$ or π , charge-parity (CP) is violated

Could this explain the origin of matter?

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

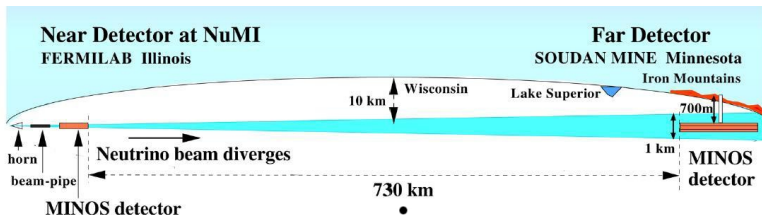
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

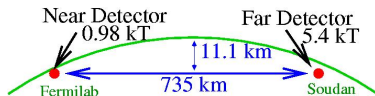


MAIN INJECTOR NEUTRINO OSCILLATION SEARCH.



Neutrinos at the Main Injector

The longest baseline accel. ν expt in operation. Average power = 320 kW.



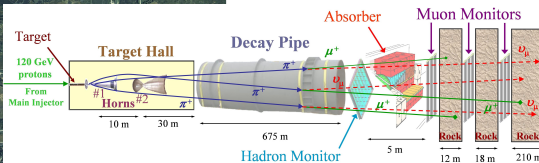
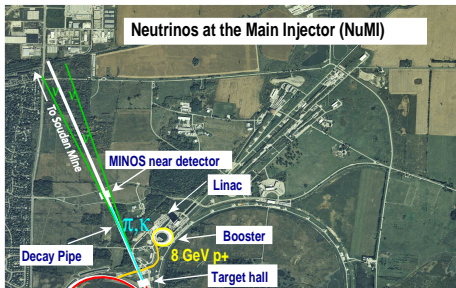
Fermi Natl. Lab., IL

Soudan Underground Lab, MN



NuMI Horn 2 inner conductor
Radial field, $B \propto 1/r$

3T at 200 kA



Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

The MINOS Collaboration

BNL: Mary Bishai, Mark Dierckxsens, Milind Diwan, David Jaffe, Brett Viren, Lisa Whitehead, Kevin Zhang

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



140 scientists, 31 institutions, 6 countries

The MINOS Detectors

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

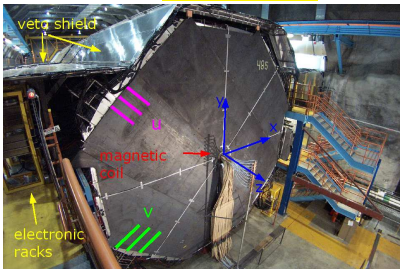
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Far Detector



Near Detector



- 484 octagonal steel and scintillator plates 8m wide,
⇒ 5.4kTon and 30 m in length .
- Magnetized
- Cosmic μ veto shield

- 282 “squashed” octagonal steel plates, 153 scintillator planes.
⇒ 1kTon and 16 m in length .
- Magnetized

MINOS Near Detector Event Display

Brett Viren, BNL, lead developer

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

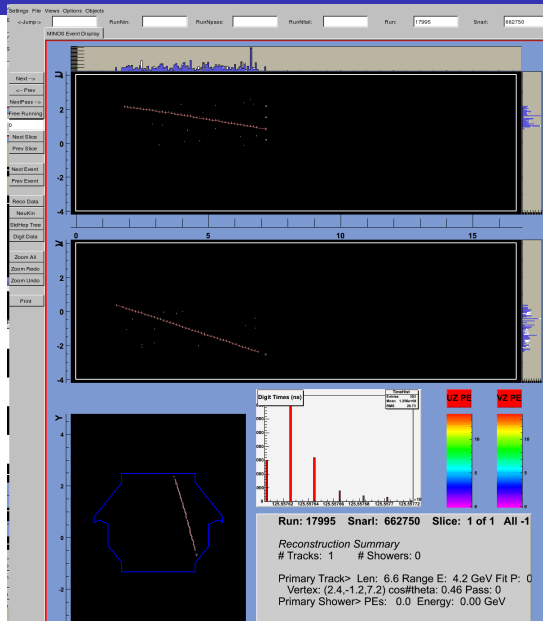
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



MINOS Near Detector Event Display

Brett Viren, BNL, lead developer

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

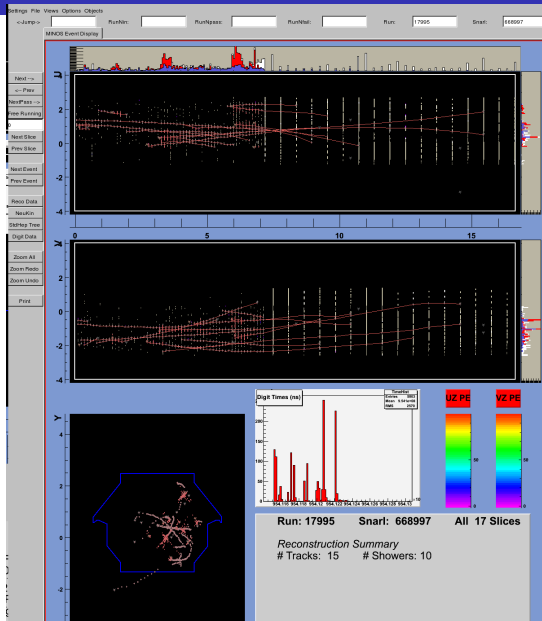
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



MINOS Near Detector Event Display

Brett Viren, BNL, lead developer

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

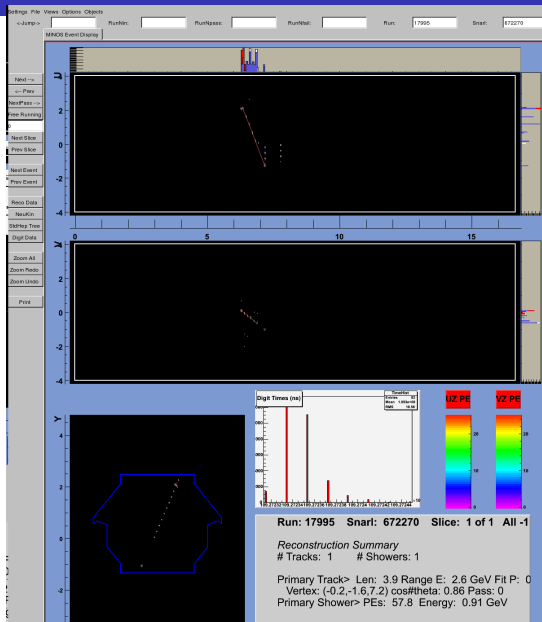
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



MINOS Near Detector Event Display

Brett Viren, BNL, lead developer

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

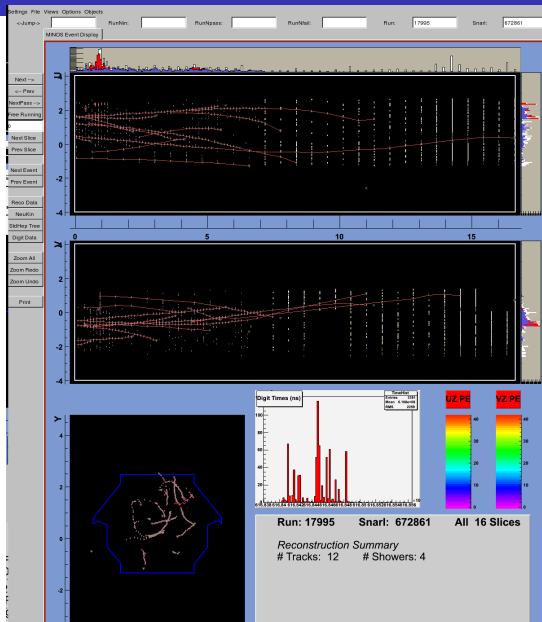
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

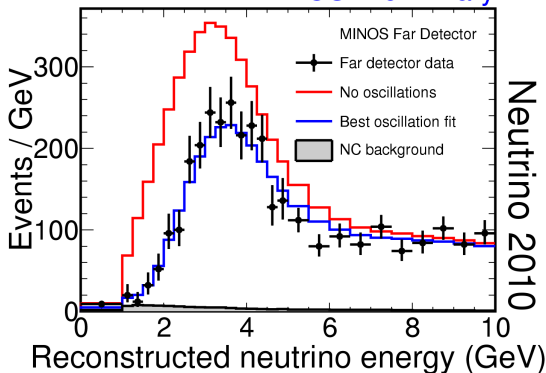
Acknowledgements



MINOS Results - 2010

ν_μ disappearance

MINOS Preliminary



Expected no-osc 2451.

Observe 1986.

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

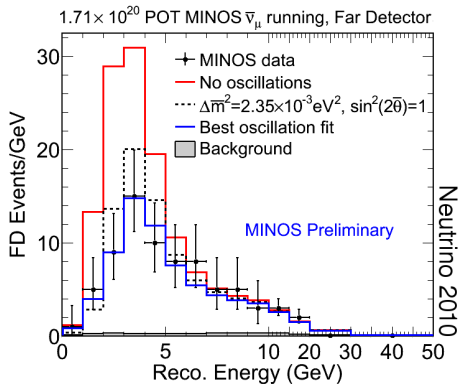
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

MINOS Results - 2010

$\bar{\nu}_\mu$ disappearance



Expected no osc 155.
Observe 97.

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

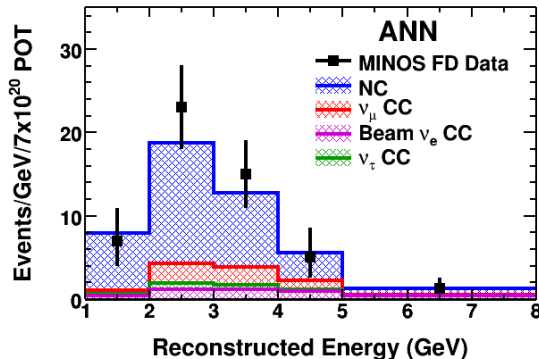
The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

ν_e appearance **NEW 2010**

MINOS PRELIMINARY



Expected FD background: $49 \pm 7_{\text{stat}} \pm 3_{\text{sys}}$.

Observe 54.

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

- M. Bishai lead the BNL effort to integrate the beamline data with the detector data. \Rightarrow **determine the absolute neutrino rate expected in the near and far detectors per proton pulse.**
- M. Bishai has been co-convener of the **MINOS Beam Systematics Group for the last 2 years.** Group is responsible the NuMI beamline simulation used to extrapolate the observed near detector ν event rate to the far detector.

Proton Target Radiation Damage

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

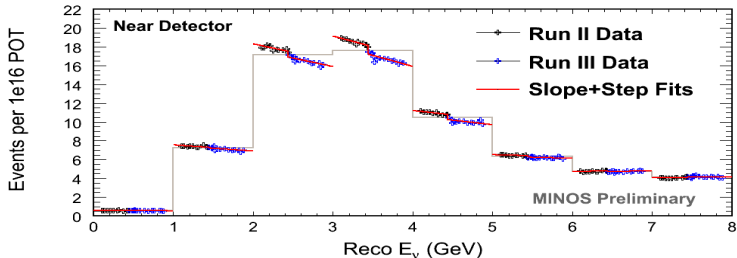
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

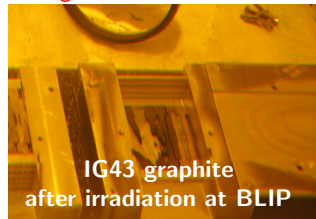
MINOS ND spectrum normalized rate vs time



Mary Bishai and David Jaffe (BNL) demonstrated that the observed drop in the ND ν rate is consistent with target damage.

Independent studies by Nick Simos

(BNL-EST) of p^+ beam irradiation damage at the BNL BLIP facility show significant damage at dosages similar to NuMI.



Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



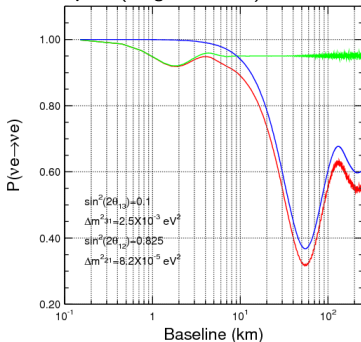
THE DAYA BAY NUCLEAR REACTOR EXPERIMENT

Attempting to measure the ν_e portion of ν_3
(AKA $\sin^2\theta_{13}$)

Short Baseline Reactor $\bar{\nu}_e$ oscillations

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m_{31}^2 L/E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(1.27 \Delta m_{21}^2 L/E)$$

Osc prob. (integrated over E) vs distance



Getting to $\sin^2 \theta_{13} < 0.2\%$

Lots of statistics: -Powerful nuclear reactors + more massive detectors

Suppress cosmic backgrounds:

-Increase overburden = go deeper underground.

Reduce systematic uncertainties:

-Use "identical" N/F detectors to reduce near/far detector uncertainties.

-Calibration, calibration, calibration...

Unambiguous measurement

of $\sin^2 \theta_{13}$

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

The Daya Bay Reactor Complex

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



Reactor Specs:

Located 55km north-east of Hong Kong.

Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW_{th}

By 2011: 2 more cores at Ling Ao II site = 17.4 GW_{th} ⇒ top five worldwide

$1 \text{ GW}_{th} = 2 \times 10^{20} \bar{\nu}_e / \text{second}$

Deploy multiple near and far detectors

Reactor power uncertainties < 0.1%

The Daya Bay Collaboration

BNL: 22 collaborators from Physics and Chemistry

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



Detecting Neutrinos from the Daya Bay Reactors

BNL Chemistry leads scintillator effort

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

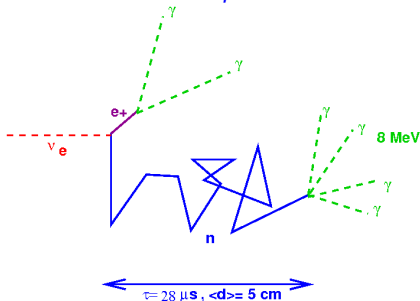
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

The active target in each detector is liquid scintillator loaded with 0.1% Gd



- $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma\gamma$ ($2 \times 0.511 \text{ MeV} + T_{e^+}$, prompt)
- $n + p \rightarrow D + \gamma$ (2.2 MeV , $\tau \sim 180 \mu\text{s}$). OR
- $n + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma\text{'s}$ (8 MeV , $\tau \sim 28 \mu\text{s}$).

**\Rightarrow delayed co-incidence of e^+ conversion and n-capture ($> 6 \text{ MeV}$)
with a specific energy signature**

The Daya Bay Experimental Apparatus

BNL Physics lead muon veto design, and US installation/integration/safety.

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

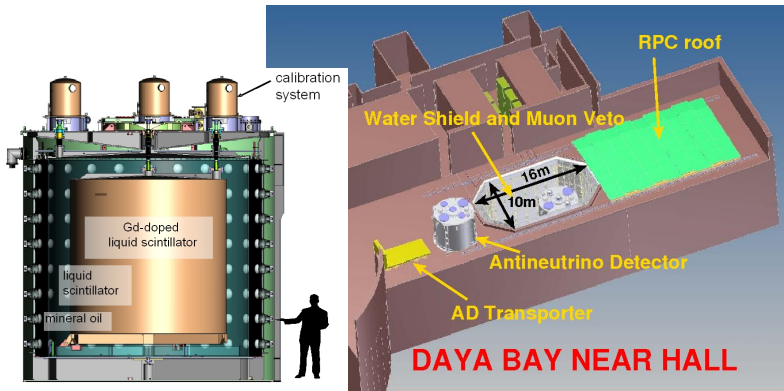
Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



- Multiple “identical” detectors at each site.
- Manual and multiple automated calibration systems per detector.
- Thick water shield to reduce cosmogenic and radiation bkgds.

	DYB	LA	Far
Event rates/20T/day	840	740	90

Daya Bay Status

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements



End 2010: Near detector ready. End 2011: far detectors ready

Reach sensitivity to $\sin^2 \theta_{13} < 0.2\% @ 90\% \text{ C.L. by 2014}$

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

THE LONG BASELINE NEUTRINO EXPERIMENT

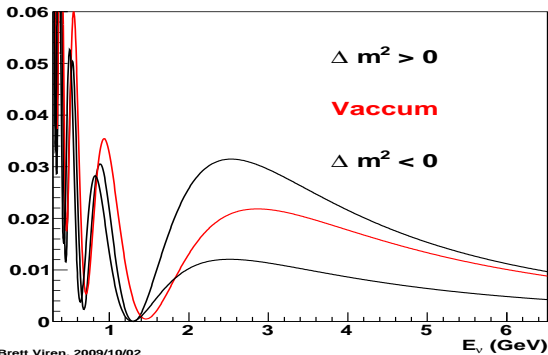
**The search for the neutrino mass hierarchy
and CP violation**

Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refractive index \Rightarrow neutrinos in matter have different effective mass than in vacuum.

For $P_{\text{osc}} = P(\nu_\mu \rightarrow \nu_e)$:

$P(\mu, e)$ at 1300 km



We can determine the mass hierarchy using $\nu_\mu \rightarrow \nu_e$ oscillations

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

The Long Baseline Neutrino Experiment

247 collaborators (36 BNL), 57 institutions. Milind Diwan (BNL) co-spokesperson

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

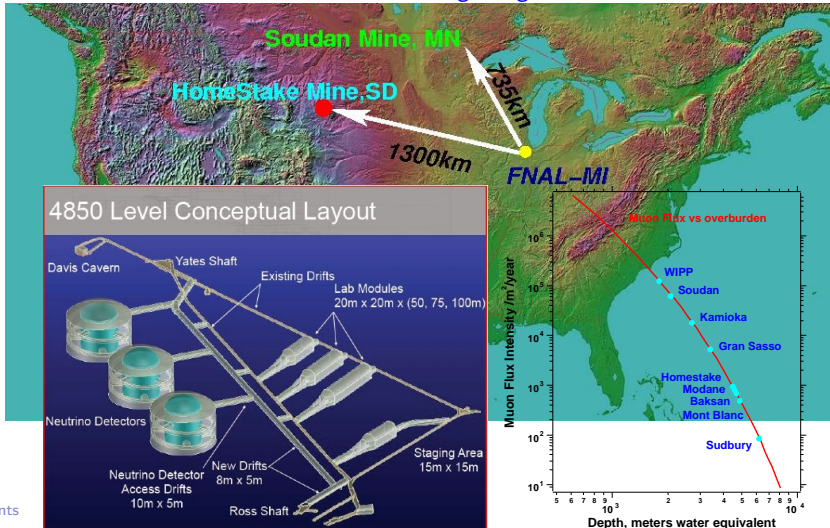
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

A Long Baseline Neutrino Experiment (LBNE) from Fermilab to megaton scale detectors at Homestake is now being designed. CDR late 2010.



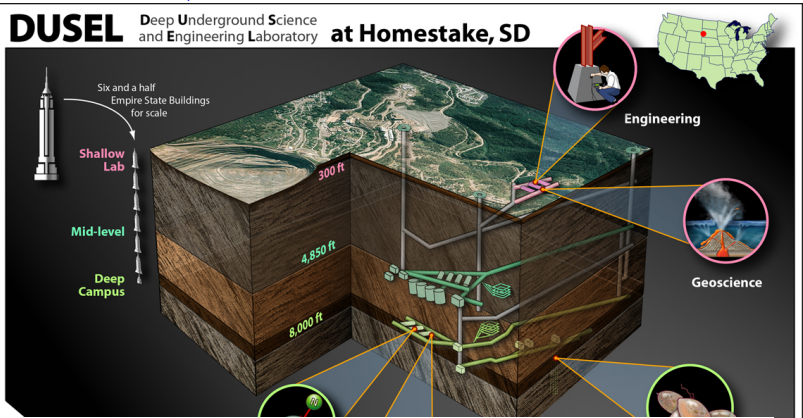
Deep Underground Science and Engineering Laboratory

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

July 10, 2007: the National Science Foundation (NSF) selected the University California-Berkeley to produce a technical design for DUSEL at Homestake Mine, SD

DUSEL Deep Underground Science and Engineering Laboratory **at Homestake, SD**



Dec 2010: National science board (NSB) preliminary design review.

FY13: Earliest construction funding if approved by NSF's NSB.

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

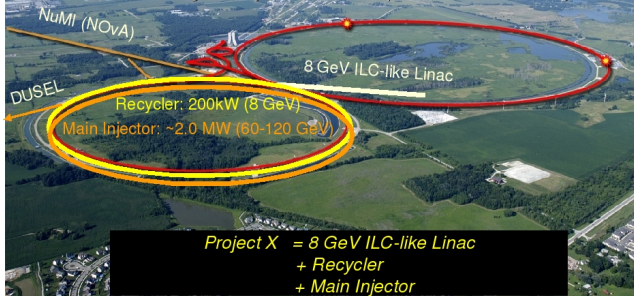
Fermilab Neutrino Beams: Future

The NuMI beamline uses a 300kW proton beam from the Main Injector (700 kW by 2012).

NuMI is the most powerful ν beamline operating today .

Fermilab vision :The Intensity Frontier with Project X:

Start with a 700-kW beam, and then take profit of the significantly increased beam power available with Project X



The proposed Project X at FNAL \rightarrow 2MW with $E_p = 60 - 120\text{GeV}$

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

DUSEL Detectors: Water Cerenkov

BNL project management, lead detector design effort.

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

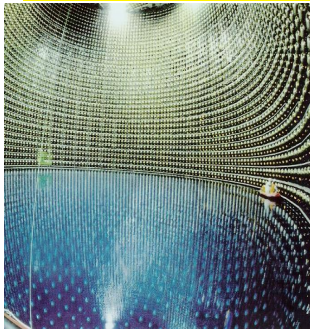
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

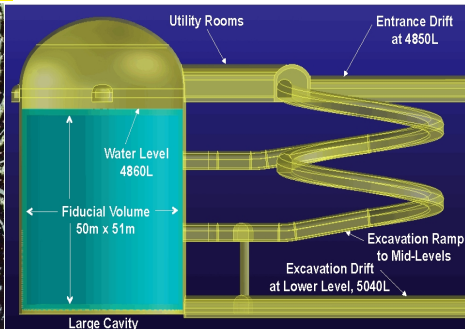
Summary

Acknowledgements

SuperKamiokande : 50kT



DUSEL WCe Module : ~ 120 kT



3 100kT (fiducial) modules, ≈ 55 m diameter, ≈ 60 m height, 60K 10" PMTs/module (25% coverage)

Known technology 3 – 4 \times SuperK

Large backgrounds, low efficiency

DUSEL Detectors: Liquid Argon TPC

BNL ITD lead effort on readout electronics

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

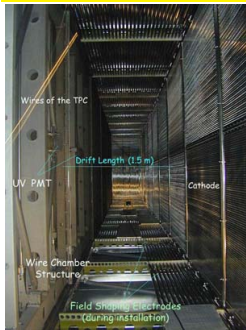
The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

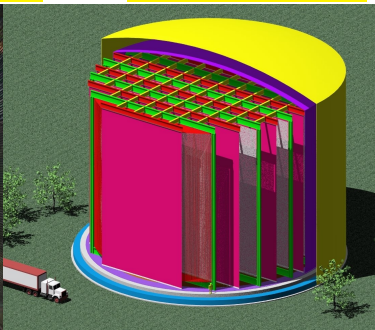
Summary

Acknowledgements

ICARUS module : 0.3kT



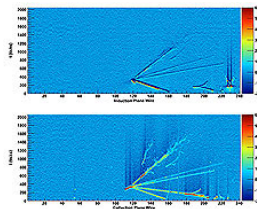
DUSEL LAr : 50 kT



**ArgoNeuT (175 litre) prototype in the
NuMI beam →**

High efficiency and purity

Requires 100× scale-up - unproven.

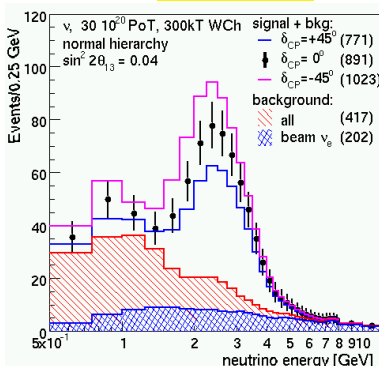


LBNE/DUSEL spectra and event rates

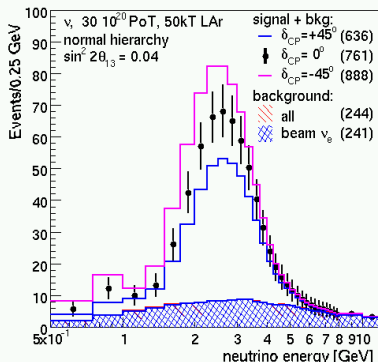
Mary Bishai, Brett Viren, Mark Dierckxsens, BNL

A preliminary on-axis wide-band beam for LBNE based on the NuMI focusing system has been developed. Water Cerenkov response is based on the SuperK MC. LAr is modeled as a near-perfect detector.
Exposure is 3 MW. yr ν with $\sin^2 2\theta_{13} = 0.04$, $\delta_{cp} > 0$, $m_3 > m_1$

300 kT WCh



50 kT LAr



Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

Summary and Conclusions

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

3 flavor neutrino mixing is now well established.

BUT- what we dont know is even more important:

- What is the mass of ν_μ ?
- Why is the mixing in the neutrino sector so large?
- How small is $\sin^2 \theta_{13}$? Is it close to the current limit (4%) or is it very small? Is it 0?
- What is the mass hierarchy?
- Is there CP violation in the lepton sector?
- Are there only 3 generations of leptons?

In the coming decades, the Daya Bay and LBNE projects will significantly extend the neutrino discovery frontier. BNL has played a critical role in past and present ν experiments and is leading the charge into undiscovered territory

Acknowledgements

Fire, Earth,
Water, Iron

Mary Bishai
Brookhaven
National
Laboratory

Neutrinos: A
History

Neutrino
Mixing

Main Injector
Neutrino
Oscillation
Search

The Daya Bay
Reactor ν
Experiment

The Long
Baseline
Neutrino
Experiment

Summary

Acknowledgements

I'd like to thank the following members of BNL's Electron Detector Group (EDG) for their invaluable support and mentorship: Milind Diwan, David Jaffe, Brett Viren, Laurie Littenberg, Steve Kettell, Mark Dierckxsens, Lisa Whitehead.

This work has been supported by DOE Office of Science

